

## Can dust destabilize galactic disks?

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### Abstract

We studied the dynamical influence of a dust component on the gaseous phase in central regions of galactic disks. Therefore, we performed two-dimensional hydrodynamical simulations for flat multi-component disks embedded in a stellar and dark matter potential. The pressure-free dust component is coupled to the gas by a drag force depending on their velocity difference.

It turned out that the most unstable regions are those with either a low or near to minimum Toomre parameter or with rigid rotation, i.e. the central area. In that regions the dust-free disks become most unstable for a small range of high azimuthal modes ( $m \sim 8$ ), whereas in dusty disks all modes have similar amplitudes resulting in a patchy appearance. The structures in the dust have a larger contrast between arm and inter-arm regions than those of the gas. The dust peaks are frequently correlated with peaks of the gas distribution, but they do not necessarily coincide with them. This leads to a large scatter in the dust-to-gas ratios. The appearance of the dust is more cellular (i.e. sometimes connecting different spiral features), whereas the gas is organized in a multi-armed spiral structure.

We found that an admixture of 2% dust (relative to the mass of the gas) destabilizes gaseous disks substantially, whereas dust-to-gas ratios below 1% have no influence on the evolution of the gaseous disk. For a high dust-to-gas ratio of 10% the instabilities reach the saturation level already after 30 Myr.

**Keywords:** Galaxies: kinematics and dynamics – Galaxies: spiral – Interstellar Medium: dust – Interstellar Medium: structure

### 1 Introduction

Chemodynamical simulations are characterized by a multi-phase treatment of the interstellar medium (ISM). In most of these calculations the ISM is split into two dynamically different components, the clumpy star-forming molecular clouds and the diffuse warm or hot gas (Theis et al. 1992, Samland et al. 1997). More refined decompositions of the ISM are only done for one-zone models (e.g. Ikeuchi et al. 1984), but not for gravitationally coupled, dynamically evolving systems. Especially, the dust component in galaxies is usually just seen as a tracer population which has no dynamical influence on galactic dynamics. On the other hand, it is well known that even a small admixture of a dynamically cold component can substantially destabilize galactic structures as Jog & Solomon (1984) demonstrated for a small amount of cold gas embedded in stellar disks. The aim of our paper is to study, whether a dynamically cold dust phase can also destabilize galactic disks.

Good places for looking on the influence of dust are galactic central regions. During the last years high resolution observations revealed that the circumnuclear regions contain stellar-gaseous mini-disks with sizes of a few hundred pc (e.g. Carollo et al. 1997). These disks have an astonishing rich structure described as mini-bars, spiral-like dust lanes, star-forming rings or spiral arms. Many nuclear regions are also well described as patchy or multi-armed. Investigations by Regan & Mulchaey (1999) showed that these spirals are the most common morphological structures in the central regions of galaxies.

Since the nature of the mini-spirals is of great importance for our understanding of a variety of astrophysical processes like the mass accretion into galactic nuclei, several explanations for have been invoked. E.g. Athanassoula

(1992) studied the gas flows in and around bars by (stellar-dynamical) orbital analysis. She found that the existence of different periodic orbit families (or equivalently the existence of inner Lindblad resonances (ILR)) is a key criterion for the existence and the shape of dust lanes.

Different to the stellar-dynamical interpretation Englmaier & Shlosman (2000) suggested that mini-spirals in central regions of galactic disks are related to the formation of grand-design spiral patterns in galaxies. They argued that gas density waves – different to stellar density waves – are not completely damped or absorbed at the ILR and, thus, they may generate spiral structures at all radii including the nuclear regions. Such a model might explain the continuity of some spiral features at small and large radii as well as the low arm-interarm contrast observed in galactic centers. A similar idea of induced structure formation is to invoke secondary bars or small nuclear bars located inside the ILR (Wada & Koda 2001).

A common property of all the mentioned mechanisms is that they result in structures dominated by two or a few arms. On the other hand, Elmegreen et al. (2002) stressed that nuclear dust spirals differ from main-disk spirals in several respects: the nuclear spirals are very irregular with both trailing and leading components that often cross.

All discussed mechanisms have some weak points and can not fully account for all the observational data. We consider here a new approach based on the observation that circumnuclear disks of galaxies are dusty. By means of a stability analysis Noh et al. (1991) showed that a dust component can strongly destabilize proto-planetary disks. The admixture of only 2% of dust enhances the growth rates of the dominant gaseous phase significantly. A conservative estimate of the dust-to-gas ratio  $r$  in the solar neighborhood

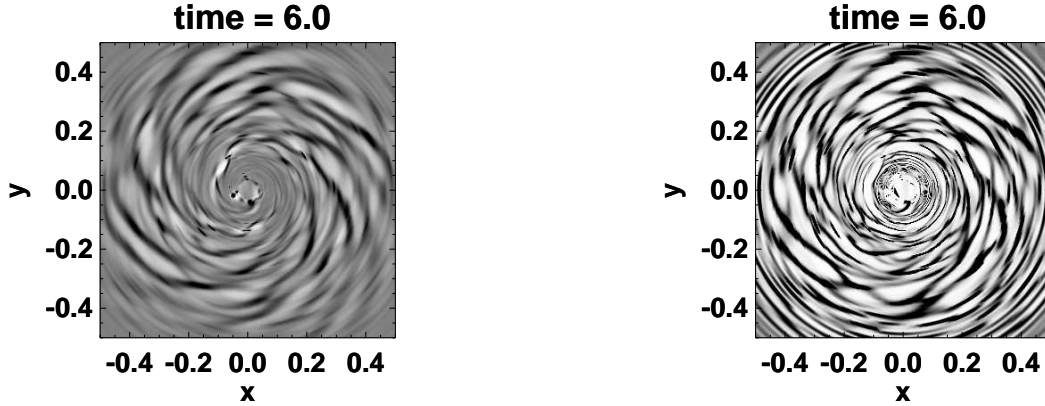


Figure 1: Perturbations of the surface density (normalized to their initial values) of the gas and dust component after  $t = 6 \sim 90$  Myr for a model with a 10% dust mass fraction (relative to gas):  $\Delta\Sigma_{g,d}/\Sigma_{g,d}$  for gas (left) and dust (right). Areas devoid of material are white, areas with a density enhancement of a factor of 2 or more are black. The grey area seen at the outer edges correspond to no deviation from the initial surface density. The lengths at the  $x$ - and  $y$ -axes are given in kpc.

gives an average value of 0.6% ranging from 0.2% up to 4% in  $H_2$  regions (Spitzer 1978). These are lower limits because large, massive dust grains do not have a detectable extinction. Direct satellite-based measurements give  $r$ -values up to 2% (Frisch et al. 1999). Little is yet known about the true dust-to-gas ratio in external galaxies, but some galaxies show large values. E.g. M51 has a dust-to-gas ratio of 2%. Taking the observed relation between the dust-to-gas ratio and the metallicity (Issa et al. 1990) into account, it is reasonable to assume larger dust mass fractions in the metal-enriched central regions of galaxies than on average.

In this paper we study the dynamical influence of a dust component on circumnuclear gaseous disks. We restrict our analysis to systems without a nuclear or a large scale bar and we do not consider any formation or destruction processes of the dust. This investigation is done by 2D multi-component hydrodynamical simulations.

## 2 Method

### 2.1 Equations of motion

We studied numerically the hydrodynamical equations for a 2-dimensional single- or multi-component disk. Thus, we solved the continuity equation

$$\frac{\partial \Sigma_{g,d}}{\partial t} + \nabla \cdot (\Sigma_{g,d} \vec{v}_{g,d}) = 0 \quad (1)$$

and the momentum equations for gas and dust. The momentum equations read for gas

$$\frac{\partial \vec{v}_g}{\partial t} + (\vec{v}_g \cdot \nabla) \vec{v}_g + \frac{\nabla P_g}{\Sigma_g} + \nabla(\Phi + \Phi_{\text{HBSD}}) = S_g(\vec{v}_g) \quad (2)$$

and for dust

$$\frac{\partial \vec{v}_d}{\partial t} + (\vec{v}_d \cdot \nabla) \vec{v}_d + \nabla(\Phi + \Phi_{\text{HBSD}}) = S_d(\vec{v}_d) \quad (3)$$

The components are denoted by  $g$  for the gaseous phase and by  $d$  for the dust.  $\Sigma_{g,d}$  are the surface densities and

$\vec{v}_{g,d}$  the velocities.  $P_g$  is the pressure of the gas which is given in the 2d-case as force per unit length.  $\Phi$  denotes the potential of the self-gravitating disk. It is derived from the Poisson equation

$$\Delta\Phi = 4\pi G \Sigma(R, \varphi) \delta(z) = 4\pi G (\Sigma_g + \Sigma_d) \delta(z) \quad (4)$$

An external potential is added by a stationary contribution  $\Phi_{\text{HBSD}}$  related to the halo, the bulge and/or a stellar disk component. These external potentials are chosen to match – together with the potential of the disk – a given rotation curve.

The main difference between the gaseous and the dust component is the treatment of the dust as a pressureless phase. Therefore, if gas and dust are in rotational equilibrium, there is a velocity difference between both components which might give rise to a non-negligible frictional force depending on the cross-section for the gas-dust interaction. This interaction is described by the source terms  $S(\dots)$  on the RHS of the hydrodynamical equations. Since we do not consider dust formation and destruction processes, the source terms in the continuity equation vanish. However, frictional terms show up in the equations of motion. The dust implementation will be described in the next paragraph.

The set of hydrodynamical equations is closed by a polytropic equation of state

$$P_g = K \Sigma_g^{\gamma_g} \quad (5)$$

For the gaseous phase we set the polytropic exponent to  $\gamma_g = 5/3$ . The constant  $K$  is chosen to yield a given minimum Toomre parameter.

### 2.2 Treatment of the dust component

The main difference between "normal" galactic disks and our dusty disks is that the cold component (dust) is not only coupled by gravity to the hotter phase (gas), but also by a frictional force between both components. This drag

is taken into account by a source term in the equations of motion following the general form suggested by Noh et al. (1991)

$$\vec{f} \equiv S_d(\vec{v}_d) = -A(\vec{v}_d - \vec{v}_g) \quad (6)$$

$$S_g(\vec{v}_g) = -\frac{\Sigma_d}{\Sigma_g} \vec{f}. \quad (7)$$

The second source term, Eq. (7), follows from the requirement of momentum conservation. The physics of the friction is enclosed in the frictional timescale  $A^{-1}$ . Based on a microscopic view of the frictional process, i.e. the momentum exchange between gas and dust particles by collisions and the equipartition of momentum within the gaseous phase, the timescales can be calculated. For the simulations shown in this paper we assumed that the dust disk is thin compared to the gaseous disk. In that case the frictional time scale is of the order of the dynamical time scale given by the inverse circular frequency  $\Omega^{-1}$  (Noh et al. 1991), i.e.

$$A = \Omega. \quad (8)$$

The basic assumption is here that gas and dust establish very fast collisional equilibrium in the thin dust layer and that the gas momentum is then mixed vertically in a sound travelling time scale (for further details see Theis & Orlova 2004).

### 2.3 Numerical implementation

The nonlinear analysis implies the solution of the full set of hydrodynamical equations. For this purpose, we developed a two-dimensional numerical code which is similar to the ZEUS-2D code by Stone & Norman (1992). The hydrodynamical equations are discretized on a logarithmic Eulerian grid in polar coordinates ( $270 \times 270$  grid cells). The different terms are treated by operator splitting. Advection is performed by a second order Van Leer advection scheme.

## 3 Results

### 3.1 Parameters of the initial gaseous disk

The characteristic values of our initial models are motivated by the nuclear region of M100 (NGC 4321). We adopted a total gas mass of  $4.7 \cdot 10^8 M_\odot$  distributed exponentially with a scale length of 300 pc within a radial range of  $R_{\text{in}} = 30 \text{ pc}$  to  $R_{\text{out}} = 3 \text{ kpc}$ . The short disk scale length mimicks a central concentration of (molecular) gas observed in many galaxies. Small random perturbations are initially superimposed on the mass distribution by multiplying the surface density in each cell with a factor  $(1 + A_R R)$ .  $R$  is a random number in the interval  $[-1, 1]$  and  $A_R$  a small amplitude of the order of  $10^{-8}$ .

The initial velocities are derived from rotational equilibrium, i.e. there is no initial radial motion. The rotation curve is specified by

$$v_c(R) = v_\infty \cdot \frac{\frac{R}{R_{\text{flat}}}}{\left[1 + \left(\frac{R}{R_{\text{flat}}}\right)^{n_t}\right]^{1/n_t}}. \quad (9)$$

The velocity at infinity,  $v_\infty$ , was set to  $178 \text{ km s}^{-1}$ . The transition parameter  $n_t$  was selected to be 10 resulting

in a fairly sharp transition at the radius  $R_{\text{flat}} = 100 \text{ pc}$ . This rotation curve corresponds to a total dynamical mass  $M_d(R) \sim v_c^2(R)R/G$  (including all components) of  $7.3 \cdot 10^8 M_\odot$  within the central 100 pc. In the region of rigid rotation the rotation period is about  $3.5 \cdot 10^6 \text{ yrs}$ . It increases outwards reaching  $1.7 \cdot 10^7 \text{ yrs}$  at the half-mass radius of the gaseous component at  $R \approx 500 \text{ pc}$ . The azimuthal velocity of the gaseous phase is calculated by the (frictionless) Jeans' equation.

According to the chosen rotation curve, mass profile and equation of state (polytropic with  $\gamma_g = 5/3$ ), the minimum value of the Toomre parameter is reached at a galactocentric distance of about 440 pc. The constant in the equation of state (for the gaseous phase) was selected to yield a minimum Toomre parameter of  $Q_{\text{min}} = 1.54$ . This choice corresponds to sound speeds between 4 and  $11 \text{ km s}^{-1}$  within the central kpc (the higher value is reached in the center).

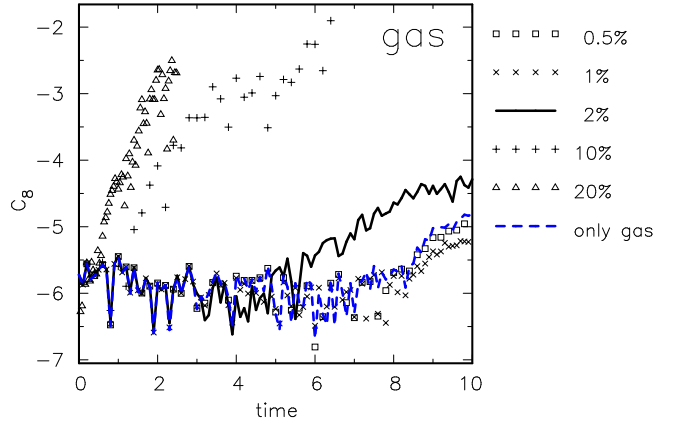


Figure 2: Temporal evolution of the logarithmic Fourier amplitudes  $C_8 \equiv \log A_8$  of the (dominant)  $m = 8$ -mode of the dust component for different dust-to-gas mass fractions: 0.5% (open boxes), 1% (crosses), 2% (reference model, solid line), 10% (plus), 20% (triangle) and the purely gaseous model (dashed line). The time unit is  $1.5 \cdot 10^7 \text{ yrs}$ .

### 3.2 A dusty disk

We studied the influence of the dust-to-gas mass ratio  $r$  by varying  $r \equiv M_d/M_g$  from 0.5% to 20%. Fig. 1 shows the surface density perturbations of gas and dust in the saturation stage of a model with a large dust-to-gas ratio: the irregular multi-armed structure is emphasized due to large arm-interarm variations. Along the arms strong surface density variations can be discerned. Some arms are interrupted by low density areas, others are not smoothly curved, but show wiggles. Some arms seem to merge with others. The dust distribution is highly correlated with the gas distribution. However, the contrast between arm and interarm regions is larger for the dust than for the gas. The surface densities of the dust vary by about one order of magnitude, whereas the contrast of the gas component is usually less than a factor of 2. The structures formed in the

dust are also thinner than those of the gas. Though there is a tight correlation between the positions of the maxima of the gas and dust phases, there is no correlation between their maximum amplitudes. The dust distribution is characterized by a more cellular appearance compared to the spiral-like morphology of the gas.

It is interesting to note that the dust is often located at the boundaries around peaks of the gas distribution, preferentially at the inner boundary. Other dust peaks are in regions with no or only weak gaseous density enhancements. And, of course, there are dust peaks at the same locations as those of the gas. Thus, one expects large spatial variations of the dust-to-gas ratio.

In order to quantify the (global) stability of the disk we use the global Fourier amplitudes of each component

$$A_m \equiv \frac{1}{M_{\text{disk}}} \left| \int_0^{2\pi} \int_{R_{\text{in}}}^{R_{\text{out}}} \Sigma(r, \phi) r dr e^{-im\phi} d\phi \right| \quad (m > 0). \quad (10)$$

$M_{\text{disk}}$  is the mass of the disk for the component of interest in the specified radial interval  $[R_{\text{in}}, R_{\text{out}}]$ .  $\Sigma$  denotes the corresponding surface density. Comparing the modes from  $m = 1$  to  $m = 16$ , the high- $m$ -modes around  $m \sim 8$  are dominant during the linear regime. A comparison of the corresponding Fourier amplitudes with those of a purely gaseous model shows that the critical dust-to-gas ratio  $r_c$  for dust becoming dynamically unimportant is about 1% (Fig. 2). For larger amounts of dust the destabilization of the gaseous phase becomes much stronger. For  $r = 0.02$  the instability sets in about 50 Myrs earlier than in dustless or low-dust-content models while the modes remain on their initial value for a latency period of about 75 Myrs. Increasing  $r$  to 10% reduces the latency time to almost zero. The growth rates increase by a factor of 3-4 and the saturation level reached already after 30 Myrs is larger by at least one order of magnitude.

A more detailed discussion on the method and the results as well as an extended parameter study can be found in our forthcoming paper (Theis & Orlova 2004).

## Summary

We studied the influence of a cold dust component on the evolution of galactic gaseous disks by means of 2-dimensional hydrodynamical simulations. From the evolution of the Fourier amplitudes we found that the higher-order modes are the dominant unstable modes. Their growth is mainly restricted to the central kpc. An admixture of 2% dust (relative to the gas mass) destabilizes the gaseous disk. The growth of instabilities in the dust component becomes non-linear after 100 Myr, followed by the gas 50 Myrs later.

The structures formed in both, gas and dust, are rather irregular and multi-armed. This is a direct consequence of the superposition of many high- $m$  modes of similar amplitude. The dust component is characterized by a much stronger contrast between arm and inter-arm regions than the gas. The dust is spatially correlated with gas, but it does not exactly follow the gas. Peaks in the dust distribution are frequently found at the inner edges of peaks in the gas distribution. This results in a large scatter of dust-to-gas ratios at different places. The dust develops also

thin filaments which sometimes connect the arms. Therefore, the dust distribution has a more cellular appearance, whereas the gas develops a multi-armed spiral morphology.

Below a dust-to-gas mass ratio of 1% the dynamical influence of the dust on the gaseous disk becomes negligible. This critical value is close to the observed mean value in normal galaxies like the Milky Way. Since the dust-to-gas ratio scales linearly with metallicity, larger local values of  $r$ , especially in the central galactic regions, seem to be reasonable. Such values are also in agreement with local gas-to-dust determinations. Since already a dust-to-gas ratio of 2% significantly affects the evolution of the disk, even the observed small dust admixtures are expected to have an impact on the dynamics of some galaxies (e.g. the dust-rich M51). For a 10% admixture of dust the gaseous component is completely destabilized. The growth rates are enhanced by a factor of 3-4 with almost no latency phase. The saturation levels reached after 30 Myr are substantially larger than in the low- $r$  calculations.

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